This Is How Elon Musk Can Build the Hyperloop for a Tenth of the Cost of High Speed Rail

Written by **JOHN GARDI**

August 6, 2013 // 09:20 AM EST

John Gardi is a tinkerer and jack-of-all-trades currently living in Canada. He garnered himself a slice of internet fame when he made a mock-up for Elon Musk's mysterious Hyperloop transportation system (http://motherboard.vice.com/blog/elon-musk-hyperloop-dream-concorde-jets-rail-guns--air-hockey-as-the-future-of-transportation), and Musk himself dubbed it the "best guess" he'd seen yet. Here, he elaborates on that guess, and explains how Musk might actually build his Hyperloop—a "cross between a Concorde and a rail gun and an air hockey table"—and do it for one tenth the cost of California's high-speed rail project. –Ed.

My small part in the Hyperloop saga began early in June when I tried to visualize Elon Musk's Hyperloop concept (http://motherboard.vice.com/blog/elon-musk-hyperloop-dream-concorde-jets-rail-guns--air-hockey-as-the-future-of-transportation) using only MS Paint and a few scattered clues.

I thought that maybe a simple infographic, bringing all those clues together in one place, would help get folks back on track. (Or is it on *tube*?) I did this mostly out of frustration with all the wild leaps that the story had been taking...and still is!

What I ended up with was a kind of flow chart, a drawing that showed what I thought Hyperloop would do, but not necessarily how it would do it. I avoided being too specific about the how part of Hyperloop for a very good reason: When Elon Musk was asked whether Hyperloop could work, his reply was that it absolutely could.

So, I'll take the man at his word that he's got 'how' covered. As Elon Musk has said about himself: "There's a pattern here."

Anyway, I posted my flow chart on Twitter a few times but it got very little traction. (That was even more frustrating!) Then Elon Musk finally dropped Hyperloop's reveal date of August 12th and asked for some feedback. I tweeted him my flow chart, not expecting

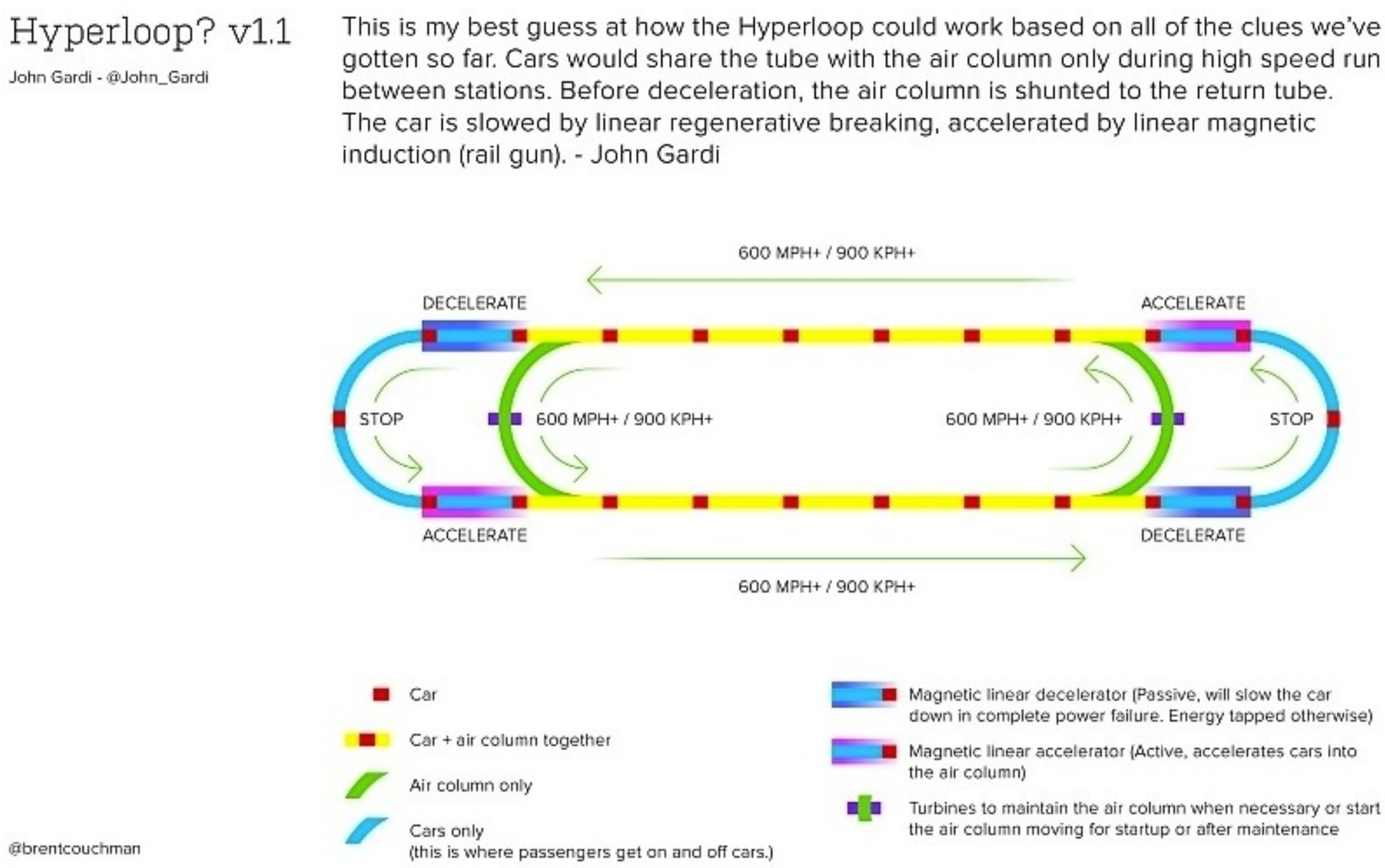
much to come of it. Very much to my surprise, he responded within minutes, saying it was "the best guess so far."

It was then I discovered just what happens to one foolish enough to stick 'is hand in a SUPERNOVA!

Many sites have posted my flow chart and I've been buried neck-deep in tweets and email ever since! But generally, I did get what I was after: critical discussion, a lot of which was a real help in formulating the ideas for this very article. Thanks go out to all of you, too many to mention.

But one of those many contacts, Brent Couchman, went the extra mile and rendered an accurate, *much* tidier, version of my original flow chart. He even said he'd take it down if I didn't like it.

Quite the contrary! Here it is for reference:



(http://assets2.motherboard.tv/content-images/contentimage/no-slug/0921dc838b76df52d0d4c9f89f7ac77c.jpg)

Tinker's original flow chart of Elon Musk's Hyperloop concept

During my heat wave, Motherboard asked me if I'd like to write an article about Hyperloop. I immediately jumped at the opportunity. At first I was going to just do a recap to try to get things back 'on tube' this way, but I've been thinking I can do Motherboard one better than that—and take the discussion a step further.

Introduction

I believe that Hyperloop is merely a modern day version of the pneumatic tubes used in banks, stores, and industry to move money and small items over long distances or to other floors of a building. They've been around for over a century, though not so much these days. There is only one in my town that I know of, and it has fallen into disuse. One reason I think Hyperloop is simpler than folks think is that Elon Musk has resurrected another technology from the depths of time, one that was a contender once, too: the electric car!

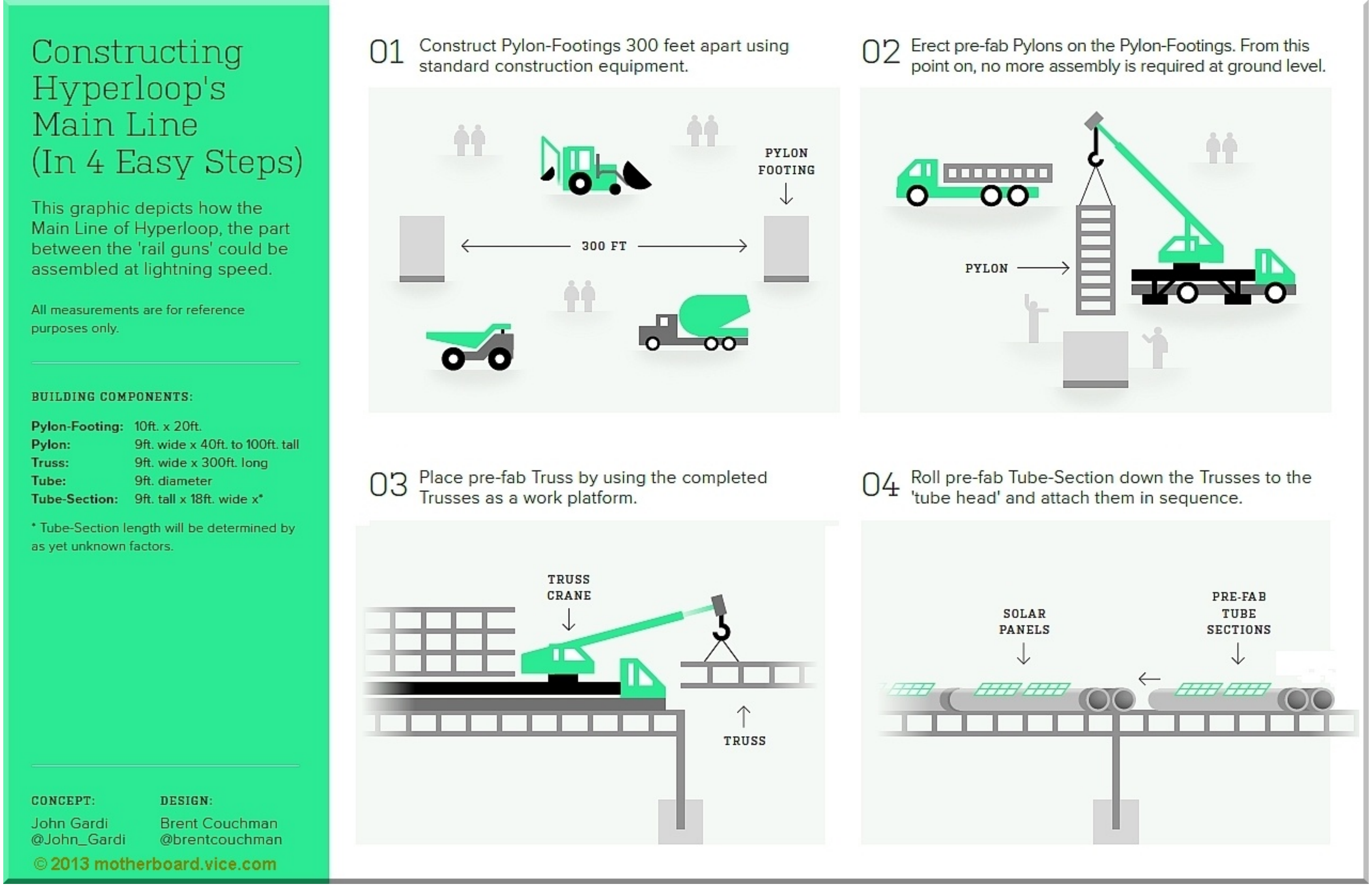
The main focus of this document will be to show how we might accomplish Elon Musk's claim that his Hyperloop concept could be built for a 10th of the cost of California's proposed high speed rail. Using technology no more complicated than warehouse building, I'll discuss how the Hyperloop's main line between Los Angeles and San Francisco might be constructed well within Musk's estimates.

I'll describe an overall design as well as construction techniques—since the main line will comprise the bulk of Hyperloop's hardware, this will be where cost reduction matters the most.

With what clues we all know now, I do believe I can make a pretty good (self) educated guess about *how* Hyperloop's main line could be built and *why* it could be done cost effectively. There's a lot we can extrapolate without having to augur down into the nuts and bolts of Hyperloop's specific technologies.

I'll leave that part to Elon Musk himself on August 12th.

But before we can even *begin* design work, we need to get a sense of scale of the entire Hyperloop system—some idea of how big to build it in the first place. Finding that sense of scale will give us the clues we need to determine *how* to design Hyperloop's main line.



(http://assets2.motherboard.tv/content-images/contentimage/no-slug/a37d627f25098b775cab8cbeb0994ce8.jpg)

The self-assembly process in 4 easy steps of the Hyperloop's main line. Illustrations by Brent Couchman

Scaling Hyperloop

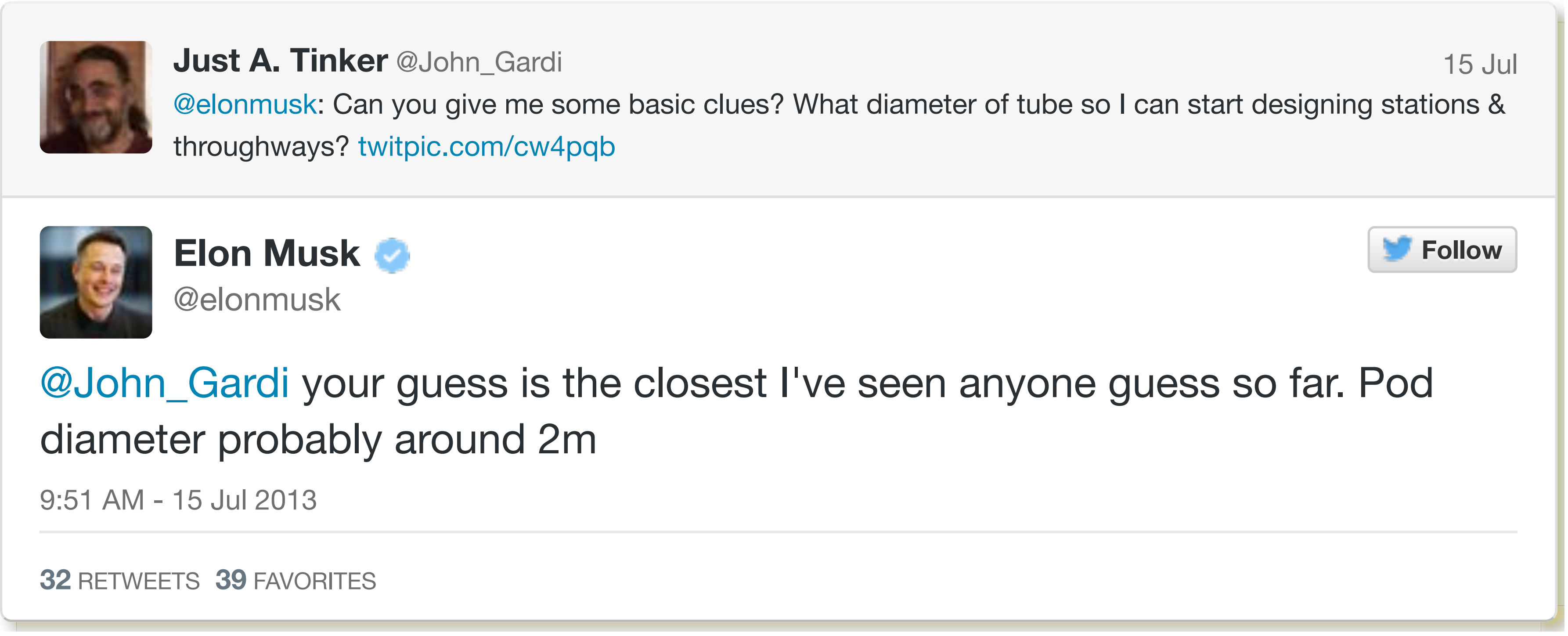
All aspects of Hyperloop's main line design will be driven by how big everything has to be made. Scale is used to describe how an object's size and/or weight relates to the world around it. The scale at which something is built also strictly determines which materials and techniques will best be suited for that particular situation. Engineering is a complex field and the scale of things is one of the main reasons for that. I should point out at this juncture that I am *not* a structural engineer myself, more civil (in both meanings of the word!).

So, what we need to do is just find some way to get a grasp on Hyperloop's scale so that we can know where to start—or we're stuck.

Scale can be used to describe the difference in size and/or weight between objects as well. In our case, we need to compare railways and Hyperloop to find the difference in scale, or scaling value: how large and/or heavy they are relative to each other.

We can use a high speed rail coach for one side of our comparison, but do we know enough about Hyperloop to find a known value for the other side? If we knew how much a single Hyperloop Pod weighed, for instance, we'd have a way to make that comparison!

But first, we need a baseline, something in common between the two that can help us find our scaling value. Luckily, Elon Musk was kind enough to give me a baseline in his response to my tweet:



Using this new clue as our baseline, believe it or not, we can now divine the scale of Hyperloop's Pods by size and weight! Using that, we can determine the scale of the entire Hyperloop transportation system.

If, as we've heard, Hyperloop pods can carry six passengers and we now know that they are six feet in diameter, we can safely assume that each pod is about the size of a family car and about the same weight too!

So it looks likes our baseline of a six-foot pod diameter has actually given us the clue we needed to make our comparison and determine the weight of a single Hyperloop pod!

Finding this out will be *very* important because the weight of the individual pods helps us determine the 'maximum loading' on the entire Hyperloop structure. This, in turn, tells us how strong everything has to be made. The maximum loading we decide upon will tell us how much weight our main line structure can have on top of it before it collapses.

We can easily work out our scaling value now! Thanks, Elon!

The weight of a high speed rail coach is approximately 40 tons. The average family car is only around two tons. Knowing this, we can extrapolate that Hyperloop could have as little as a 20th the maximum loading of high speed rail. If we choose our maximum loading value to be a 10th of high speed rail instead, our building components would be twice as strong as they need to be!

In terms of safety, this is golden!

So, for the purpose of this discussion, we'll use that value—a 10th the maximum loading of high speed rail—because we probably can afford to, but also because we can't afford not to, considering where we intend to build.

Our chosen maximum loading value seems to jive nicely with that 10 percent cost claim of Elon's too...with a high margin of safety as a bonus! So far, so good!

The maximum loading value drives the whole design process from this point on. We should *now* be able to determine the best economic, materials and, *especially*, logistic choices with which to build Hyperloop's main line.

How Railways Are Built

But first, to give you some perspective, let's take a quick look at how a traditional railway is constructed.

Workers must go over the same worksite many times:

- first, to clear, span and blast a right-of-way,
- then to engineer drainage,
- then to grade
- and, finally, to lay down the tracks.

Each and every step of the way is energy, labor, and equipment intensive. Many different types of heavy machinery are needed as well, expensive to buy and maintain. Megatons of materials have to be moved around and that costs money too, even if it *is* by rail.

Railway construction sites are often also called railheads, and are quite literally the end of the line. The railway leading to the railhead makes it very easy to get supplies and labor just to where it's needed most. This is sometimes called bootstrapping. By building the

railway in front of themselves, the construction workers are metaphorically pulling themselves up by their own bootstraps, as it were.

It's also the *only* construction technique I've adopted from the rail industry for my design—with improvements, big ones!

The Economics

Any big project needs a good business plan from the very beginning to succeed. The economic planning behind the overall design is the most important factor determining success or failure. Choosing the wrong design from the start could lead to financial ruin. Overlooking a counter-intuitive design means you might miss out on major cost savings.

The economics behind a design should be solid, not before the shovel hits the dirt, but before the pointer hits the CAD screen.

The business plan I've chosen is to leverage our low maximum loading value so that Hyperloop can not only outperform high speed rail but out-bid it in the marketplace by an order of magnitude—or more, fair and square!

My choice for a potentially successful Hyperloop main line design for is an elevated right-of-way along its entire length. This is my 'killer app' for reducing the overall costs of the main line portion of Hyperloop. The primary reason this might work is that Hyperloop's much lower maximum loading value opens up new materials and construction techniques simply not available to the rail industry.

Having an elevated Hyperloop main line also completely avoids or reduces many of the pitfalls of ground-level right-of-ways, and opens up some new opportunities as well:

- The crossing of other right-of-ways, like roads and railways, will be a breeze.
- Rivers and other terrain obstacles will only be a 10th the problem of rail construction.
- Hyperloop can avoid tunnels completely by having more flexible choices of right-of-way.
- An elevated right-of-way opens up new route options, like leasing farmer's fields using contracts similar to what wind-power companies sign.
- That could be paid for by leasing Hyperloop's right-of-way to communications companies for fiber optic cables, cell phone towers, etc.
- ...and let's not forget the solar power that a couple of square miles of surface area can generate!

I could go on, but I think you get the picture. Building Hyperloop's main line elevated could not only reduce construction costs, but provide ways to monetize the right-of-way beyond just moving folks from one place to another.

I'll use only four major building components for my Hyperloop main line design:

- Concrete pylon footings set into the ground every 300 feet* or so.
- Pylons that go on top of the pylon footings, 40 feet tall to 100 feet tall.
- Trusses that span the tops of the pylons, 300 feet long, 9 feet wide.
- Finally, tube sections, that rest atop the trusses, 18 foot wide, 9 foot tall, length unknown (due to as-yet undetermined factors).

(*Measurements for reference purposes only).

The tube sections are the real star of this show. These are the twin tubes and their associated hardware, like solar panels and such, that are the business end of Hyperloop.

Now would probably be a good time to address earthquake mitigation. Put simply, I easily found engineering solutions for each of our four building components and some dynamic ones too. So, like Elon's specific Hyperloop technologies, I can safely leave the how of earthquake mitigation to the experts. I consider the issue a done deal—and our 100 percent safety margin doesn't hurt us any either!

Building an elevated Hyperloop main line can open up still *more* ways to reduce costs by taking advantage of standardization, modularization and pre-fabrication techniques:

- We can standardize components from the pylon footings up.
- Modularizing components into subcomponents would allow everything to be shipped by truck to our staging and assembly areas. (SpaceX gave me that idea!)
- Being able to ship by truck means components could be farmed out to multiple medium-sized factories, which should help firm up the supply chain some.
- Ground-level construction is limited to the excavating and pouring the pylon footings. They should be simple enough so that we could utilize local concrete contractors.
- Once the pylon footings are complete, everything else is from then on is just crane work. (Very interesting crane work!)

So far, we've seen nothing but economic advantages by building our Hyperloop main line elevated, over railways themselves and railway construction too:

- Based on our scaling value, given to us by Elon Musk, materials by volume shouldn't be over 10 percent that of rail construction at the very least,
- Materials by cost, on the other hand, will be higher, but because there's less of it, shipping and final assembly costs should be much lower!
- By minimizing ground-level construction, we can reduce labor and materials costs *big time!*
- Workers wouldn't have to go over the same work-site nearly as often as in rail construction.
- We can monetize beyond just moving folks around to help cover operating costs!
- We need only four major building components. Economies of scale, where mass producing near identical parts lowers manufacturing costs, help us here.
- We can modularize our building components to our advantage. Linked with economies of scale, this can provide the basis for a robust supply chain.

From an economic standpoint alone, building an elevated Hyperloop main line seems like a pretty good direction to go (pun intended).

OK! Let's take that direction then and see where it leads us, so that we can *get* those shovels into the ground—for what little shoveling we'll be doing, that is!

The Materials

Before I discuss my materials choices—or lack thereof—I'd like to point out something I discovered while doing research for this article. I was cryptic before about the amount my design should save on materials volume because I found that my original estimates were way off! It was foolish of me to think that my material's volume would be 10 percent that of rail construction. It's actually about a magnitude lower!

Railways are heavy. Under those visible rails and ties, which are heavy all by themselves, are:

- tons and tons of gravel to provide good drainage,
- waterworks to make sure the rail-bed isn't eroded away,
- trestles that have to be built to withstand hundreds of tons of loading
- and let's not forget tunnels, the bane of railway construction budgets everywhere, and the megatons of materials they displace.

Compared to railways, Hyperloop's main line would be an ultra-light transportation system!

I'll have to admit, I'm open to suggestions for what types of materials to use for most of our building components. Hey, a footing's a footing. It's concrete! Ditto for the pylons and trusses too. Lots of choices out there.

Way back when, for a commercial drafting class in college, I designed a warehouse that spanned a little less than the 300-foot distance between our pylons. A single truss from that design had a maximum loading value twice that of what's needed for ours.

So, that leaves just one building component left to go—the tube sections—which I actually *do* have a suggestion for:

Lightweight composite sewer pipe!

Lightweight composite sewer pipe, 11 feet in diameter, is easily handled by standard equipment.

Look, we knew from the get-go that we were gonna be stuck inside an oversized drain pipe for half an hour anyway, so why not use a real one? (New, of course!) But seriously folks, it really does make a lot of sense. We need strong, lightweight tubes. Lots of them! Pipeline manufacturing companies are only just now experimenting with pipe diameters smaller than what we need, so that's out. Someone suggested using new super-strong formulas of concrete, but I think that would be overkill and dip into our generous safety margin as well (which I'm loathe to do!).

Lightweight composite sewer pipe already exists in diameters larger than what we need (see image above). Composites can easily be added to, modified and adapted to our special purposes in a free-form way. (Hint: glue stuff to it!) If these sewer pipes can handle twenty feet of dirt and the vehicles on top of that, they will take anything Hyperloop can throw at them, as we know it surely will! Thousands of miles of this stuff gets buried in the ground every year.

It has potential. It's available *now!*

Oh, did I mention that lightweight composite sewer pipe is affordable?

Now that we have at least some ideas about what materials are needed to construct Hyperloop's main line, how can we make good logistic decisions that optimize for cost reduction during the construction process?

The Logistics

Logistic planning is where we bring everything together. Contingency is where you plan for when things go wrong. If you can't plan *for* something, plan around it instead so that it never happens in the first place! But be forewarned, if you don't plan for contingencies, you will get bitten!

I can't emphasize how much good logistic planning matters to the bottom line at every stage of a big project, especially during the construction/assembly phase.

Seamless deployment is the reward of a good logistic planner.

One example of how we can logistically optimize for cost reduction is to build flexibility right into our components:

- Custom fabrication of variable height pylons could reduce the impact at ground-level by requiring far less ground preparation work.
- The greater the difference between the shortest and tallest pylons, the more flexibility there will be in choosing an economical right-of-way.
- Our low maximum loading value suggests that the pylons could be up to 100 feet tall and still be affordable (with a 70-foot pylon height being the best fit value, the most economical average height in this case).
- We can't expect a perfectly straight-line run between Los Angeles and San Francisco either, so our trusses will need custom fabrication too.

- Trusses could be of variable lengths as well, if that helps reduce overall costs.

Being the 21st century and all, I don't think any of this will be a problem. For environmental and economic reasons, we really should place the pylons as far apart as possible without compromising safety:

- Railways rip a ground-level right-of-way straight through anywhere they need to go, destroying everything in their path to do it! 'nough said!
- Compared to rail, an elevated right-of way would have minimal environmental impact on the ground and in the air too! Unlike a wind turbine, Hyperloop has no external moving parts. (Note to Elon: consider Hyperloop bird sanctuaries…)
- The further apart the pylons are, the less ground-level work to do and less materials are used, proportional to how many times the main line touches the ground.

I should point out that reducing material costs by being able to span those long distances between pylons is just one reason to use our trusses (which might, at first glance, appear to be redundant).

There's other optimizations I could mention, but they *all* pale in comparison to the cost reductions achievable from our killer app's role in the actual assembly process of Hyperloop's main line!

How to Build a Hyperloop

The actual assembly of Hyperloop's main line is really quite simple*:* After the concrete pylon footings are poured and the Pylons erected on top of them, final assembly of the main line can leave ground-level entirely!

The killer components of this logistical high-wire app are those seemingly unnecessary load-bearing trusses.

But surely, you say, the tube sections could be made to support themselves, so why bother going to all the trouble and expense?

Here's why: Once the very first truss spans the tops of two installed pylons, we have a ready-made work-platform from which to build the rest of Hyperloop's main line. It's now that we'll leverage that centuries-old tradition of building railways by their own bootstraps—except that we'll be able to lay trusses and tube sections a hundred times faster!

First, we'll put a mobile flatbed on top of the trusses with a long crane attached to the front. We'll call it a truss crane, a specially-made self-loading vehicle that can carry completed trusses for installation between our finished pylons. It will move along the tops of the previously installed trusses themselves, just like a railcar!

Once the truss crane reaches the tube-head at the end of the last installed truss,

- It plucks a truss from the flatbed behind it,
- places the truss so that it spans the two pylons directly in front of it,
- secures it (by however means),
- rolls out onto the newly installed Truss to the next pylon.
- Repeat!

Trusses would be shipped by truck in short sections to staging areas every truss crane load along the right-of-way (whatever best fit value works). They are then assembled into full-size trusses. When the truss crane installs the last truss of its load, another load of pre-assembled trusses is waiting for it at the foot of the pylon it's located at. The truss crane only has to stop long enough to reach down, grab, and then transfer the trusses onto its flatbed.

Handle logistics *just* right and that's the longest the truss crane will have to stop during the entire main line assembly process!

The speed of laying trusses is limited only by the speed of the crane and the efficiency of the supply chain.

After all the trusses are installed, the pre-fabricated tube sections are placed atop the trusses from more centralized staging areas. Since we already have a fully functional right-of-way along the whole length of our main line, the staging areas for the tube sections can be a best fit to our advantage (whatever that happens to be). Once in position atop the trusses, the tube sections would be rolled down the main line's right-of-way to their final destination, connected together in sequence and, finally, locked down.

The tubes sections would use the same guideways that the truss crane uses to install the trusses themselves!

Assembly of the Hyperloop's main line is now complete!

You see? Simple!

There you have it. That's my rationale for using the trusses. By adding an extra component to the overall design, we'd *save* money over the entire project and not just the construction phase either! Those trusses would more than pay for themselves by an order of magnitude compared to *any* other construction method!

Let me count the ways…

- The trusses are the work platform for the truss crane so that we can utilize the bootstrap method.
- The ungainly tube sections can now be easily deployed to their final destination down a finished right-of-way.
- Since the truss cranes and tube sections share the same guideway, then conceivably both parts of assembly could take place at the same time.
- *Every* single tube section could be removed and replaced as easily as they were installed when new, better technology comes along (as we surely *know* it will!).

So you see, by incorporating the trusses into the design from the beginning of the design process, construction, maintenance and even complete replacement of all the tube sections becomes so much easier, quicker and cheaper!

And basically, that's it! My killer app—using an elevated Hyperloop main line right-of-way—was not some exotic technology, but actually just a logistics scenario for assembly that was built right into the final product all along!

If we can coordinate the bootstrap method with well-organized staging areas and some good supply management, then Hyperloop's main line would not only be ultra-light, but ultra-fast to assemble as well.

The lesson here? Good logistic planning trumps materials costs any day!

Feasibility?

Now, just how feasible is this design and method of construction? I didn't find *any* show-stoppers. Solutions for all the individual aspects of my design are out there. I found them easily. You can too. It's called Google.

Building an elevated Hyperloop main line should be no more complicated than building a warehouse, except that our warehouse just so happens to be twenty feet wide and hundreds of miles long! Since there's never been a need to build a warehouse by bootstrapping it, we *are* in new territory here, but it's certainly not insurmountable.

I found cost efficiencies everywhere I looked too. Even adding a component—the trusses—brought the (estimated) bottom line for construction costs down by an order of magnitude... and, incidentally, increasing the costs of materials by a lot less!

Call me eccentric, but I've always considered cost savings, regardless of how I (honestly) achieve them, to be among my many definitions of profit!

As for the self-assembly part of my Hyperloop main line design? I'll paraphrase my own quote from the end of Brian's article (http://motherboard.vice.com/blog/elon-musk-hyperloop-dream-concorde-jets-rail-guns--air-hockey-as-the-future-of-transportation) for my answer to that one!

"Will self-assembly work as a construction method for Hyperloop? The only show stopper I can see is the first word in that last sentence!"

So, having said *that*, I'll step out on a limb here (I do it all the time. It's not so bad.). Building Hyperloop's main line for a 10th the cost of high speed rail is not only *feasible*—it's doable!

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TOPICS: hyperloop (/tag/hyperloop), elon musk (/tag/elon+musk)